Effects of Electrode Surface Topography on Aluminum Resistance Spot Welding

Electrode face topography is found to significantly influence resistance heat generation and electrode cooling effects

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ABSTRACT

Automotive lightweighting is one of the most important means to achieve the mandatory fuel efficiency requirements as established in the Corporate Average Fuel Economy Standards (CAFE), USA. To achieve this goal, lightweight materials such as aluminum alloys are utilized to fabricate vehicle bodies. However, the surface oxide found on aluminum alloy components poses significant challenges to traditional resistance spot welding (RSW) processes. This has driven many automotive manufacturers to apply self-piercing riveting as the preferred aluminum assembly joining method. To enable RSW as a common joining process for steel or aluminum body structures in a single body shop, General Motors (GM) previously developed electrodes with weld face designs that include sharp radii of curvature and surface topographies to mitigate the effects of oxide layers on aluminum alloys by reducing contact resistance. This paper explores, through microstructural analysis and mechanical property testing, the effect of electrode weld face topographies upon the resistance spot welding of 1.2-mm-thick 6022-T4 aluminum sheets welded to itself. For comparison, three types of electrode face designs were systematically studied: A textured electrode and a Multi-Ring Domed (MRD) electrode having two ring heights (e.g., Ring H1 and H2). The results indicate that the electrode face topography can significantly influence resistance heat generation and electrode cooling effects, as well as produce welds with unique morphology, microstructure, and mechanical properties.

KEYWORDS

- Resistance Spot Welding • Al Alloys • Mechanical Properties • Weldability
- Electrode Surface Topography

Introduction

The application of lightweight materials such as aluminum in automotive body structures is a strategic approach to achieve the mandatory fuel efficiency requirements as established in the Corporate Average Fuel Economy Standards (CAFE), USA (Ref. 1). When used to replace steel, aluminum alloy components can achieve mass reductions of 30 ~ 40% (Ref. 2). For example, the Cadillac CT6 is 218 lb lighter than an equivalent steel vehicle because of the advanced manufactur-

ing methods combined with a mixed material structure that includes all aluminum exterior body panels (Ref. 3). Conventional steel bodies use resistance spot welding (RSW) for assembly of the body structure. The use of the same equipment to weld aluminum (Al) to Al joints would provide manufacturing flexibility and save significant floor space and cost. However, the surface oxide layers found on aluminum alloy components pose significant challenges to traditional RSW processes. This has driven many automotive manufacturers to apply self-

piercing riveting (SPR) as the preferred aluminum-assembly joining method. SPR is an effective process to join aluminum alloys; however, it does add cost and mass to the process as well as introduces a third body that affects the electrochemical potential of the joint (Ref. 5).

Resistance spot welding is a complicated process coupling mechanical, metallurgical, thermal, and electrical phenomena (Ref. 5). It has been widely used to join steels in the automotive industry because of its inherently low cost, as well as high throughput, automation level, and adaptability (Ref. 6). However, RSW of aluminum alloys faces significant challenges because of its high thermal and electrical conductivity, high coefficient of thermal expansion, low melting temperature, and oxide layers that form on the metal surface. Because the thermal and electrical conductivity of aluminum alloys is approximately 3× that of steels, significantly higher currents have traditionally been applied though welding times one-fourth to one-third of that used for steel RSW (Ref. 7). To avoid excessive heating at the electrode/sheet interface and possible external weld metal expulsion, significantly larger weld face diameters and radii of curvature have been used, which drives wide flange requirements while reducing process robustness. Furthermore, accurate control and synchronization of current and electrode force are required due to the narrow weld temperature range (Ref. 8).

Most important of all, the presence of oxide layers on the sheet surface induces a dynamic contact resistance at

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Fig. 1 — Electrode weld face profiles extracted from laser confocal 3D measurement: A — Textured; B — MRD Ring H1; C — MRD Ring H2.

Fig. 2 — Test specimen dimensions: A — Tensile shear; B — cross tension; C — coach peel. Note: all units are in mm.

welding, which complicates the generation of heat in and around the weld, and causes variability in weld quality because the oxide layer is nonuniform. Owing to the high thermal and electrical conductivity of aluminum alloys, the contact resistance at the sheet/sheet faying interface makes the primary contribution to forming a weld nugget. Unfortunately, the electrode/sheet contact resistance generates excessive heat around the electrode, resulting in wear as well as a lack of consistency and robustness during spot welding (Ref. 9).

There are many factors that influence contact resistance in the RSW process, including the sheet surface condition, mechanical interactions, and welding schedule. Al Naimi and Al Saadi (Ref. 10) investigated the influence of surface pretreatment on the RSW quality of AA1050 sheets with three thicknesses and compared welding of the as-received sheet with the pretreated sheet by either pickling in NaOH or glass blasting. They pointed out that contact resistance was drasti-

the electrode/sheet interface and the

sheet/sheet interface during spot

cally reduced by glass blasting, which removed the original oxide film and provided a rough surface to break down the oxide layer through asperity deformation. However, both pickling and glass blasting add an additional processing step, reducing productivity in practice.

Arrington (Ref. 11) twisted the electrode to remove the oxide film and the contaminants on the aluminum sheet surface before welding to improve electrode life and weld quality. However, this added time to the weld cycle to rotate the electrode, and added complexity to the robot programming to synchronize the electrode rotation with the weld gun movement.

To increase the electrode life, DeltaSpot, developed by Fronius, uses a continuous tape running between the electrode and sheet to improve welding efficiency by additional process heat that arises from both the internal and contact resistance of the process tape (Ref. 12). However, the continuous tape feed is a consumable that increases the processing cost. Crinon and Evans (Ref. 13) reported that even a small amount of induced sliding combined with pressure on specimens can displace surface films to produce a large increase in metal-to-metal contact, which causes a dramatic reduction in contact resistance. Nevertheless, this concept is difficult to implement because the panels are generally fixed in position while the body-in-white (BIW) structure is assembled.

Luo and Ao (Ref. 14) studied a preheating treatment within the weld schedule designed to reduce the contact resistance at the faying interface by two orders of magnitude. However, this would drive considerable work to optimize welding parameters to meet the varied oxide films on the surface of commercial aluminum sheet combina-

Fig. 3 — Photos of experimental setup (clamp, test specimen, extensometer, and coupon fixture for cross-tension testing) prior to application of load: A — Tensile shear; B — cross tension; C — coach peel.

tions. Moreover, they did not indicate whether preheating affected the electrode/sheet contact resistance, which is the primary reason for excessive electrode wear, surface expulsion, and inconsistent weld quality. Increasing the electrode weld face surface roughness is an unusual method to reduce the electrode/sheet interface contact resistance (Ref. 15). An electrode with a microtextured weld face, referred to as the textured electrode, was created by blasting with coarse grit using high-pressure air to obtain a surface roughness of $R_a = 5 \mu\text{m}$. However, replacing cutterblade-style tip dressers with small grit blasters throughout the body shop is not a desirable solution to maintain on a manufacturing shop floor.

The GM-patented Multi-Ring Domed (MRD) (Refs. 16, 17) electrode was created by using a uniquely designed dressing blade to produce a series of concentric ridges/grooves on the electrode weld face. The individual ring is intended to plastically deform and penetrate the aluminum oxide surface. Multiple rings in action can fracture the surface oxide by produc-

ing alternating patterns of tensile and compressive surface strains. Fracture of the surface oxide allows for intimate contact between the electrode and aluminum alloy substrate, thereby reducing the electrode/sheet contact resistance and improving heat transfer between the electrode and sheet. As a result, heat distribution during spot welding changes tremendously.

This paper explores, through microstructural analysis and mechanical property testing, the effect of electrode weld face topography upon the resistance spot welding of 1.2-mm 6022-T4 aluminum sheets welded to itself. For comparison, a common electrode geometry with three types of weld face topographies were systematically studied: A textured electrode and a MRD electrode employing two ring heights, Ring H1 and H2.

Experimental Procedure

Aluminum alloy AA6022-T4 sheets of 1.2 mm thickness were the basis for this study. The nominal chemical composition and mechanical properties for

Table 1 — Chemical Composition and Mechanical Properties of AA6022-T4

Material	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation Rate (%)	Alloying Elements (wt-%)								
				Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6022-T4	297.0	202.2	22.4	0.8–	0.05–	0.01–	0.02–	0.45–	0.10	0.25	0.15	Bal.
				1.5	0.20	0.11	0.10	0.7

Fig. 4 — Typical polished cross sections of the RSW nuggets for various electrodes: A — Textured; B — MRD Ring H1; C — MRD Ring H2. Graphical representation of the experimental weld characteristics are included.

Table 2 — Indentation Diameters for the Top and Bottom Indentations (mm)

Electrodes	Textured	MRD Ring H1	MRD Ring H2
Indentation diameter	7.39/7.39	7.94/7.72	7.38/7.87

this alloy are provided in Table 1. No surface cleaning procedures were conducted, and all testing was completed with sheets in the as-received condition.

All electrodes were conventional C15000 with a nominal composition of Cu-0.15 wt-% Zr. The textured and MRD Ring H1 electrodes had a body diameter of 19.05 mm and a 12-mm weld face, while the MRD Ring H2 electrode was somewhat smaller at 16-mm outer diameter with a 10-mm-diameter weld face. All electrode weld faces were dressed to a 25-mm radius of curvature. The various electrode faces in this body of work were characterized using a Keyence model VR-3000 laser confocal 3D imaging system — Fig. 1. According to standard

ISO 4287:1997 (Ref. 18), the profile arithmetic average error R_a was chosen to represent surface roughness. The textured electrode weld face had an approximate R_a of 5 μm — Fig. 1A. The 12-mm-diameter weld face of the MRD Ring H1 (Fig. 1B) enabled five relatively shallow rings (average ring height of 80 μm) to be dressed, while the smaller weld face of the MRD Ring H2 (Fig. 1C) had four, although these were taller rings (average ring height of 200 μm).

The welding system contained both an inverter direct current (DC) and a single-phase alternating current (AC) weld control. Transformers included a medium-frequency DC (MFDC) unit rated at 170 kVA, 13 V maximum, and

an AC unit rated at 400 kVA, 29 V maximum. The actual weld schedules followed the Conditioning, Shaping, and Sizing (CSS) weld schedule concept (Ref. 19), which is listed below. Preheat as well as squeeze and hold times were kept constant for all welds, and a 700-lb electrode clamping force was applied. Slight changes in the peak current level of the sizing portion of the CSS weld schedule were necessary to accommodate the changes of the electrode face design and achieve the targeted 5.5-mm-diameter weld nugget.

- Preheat — 700 lb: 40 ms at 6.9 kA rms, cool 10 ms
- Textured electrode — 700 lb: weld 101 ms at 27.5 kA rms, hold 100 ms
- MRD Ring H1 — 700 lb: weld 101 ms at 27.8 kA rms, hold 100 ms
- MRD Ring H2 lap shear, coach peel — 700 lb: weld 101 ms at 27.5 kA rms, hold 100 ms
- MRD Ring H2 lap shear, cross tension — 700 lb: weld 101 ms at 27.8 kA rms, hold 100 ms

Metallurgical analysis was performed on tested and untested specimens by cross sectioning along the centerline of the weld nugget. Specimens were hot mounted in resin powder and mechanically ground and polished. For metallographic analyses, the specimens were etched using Keller's reagent (95 mL water, 2.5 mL HNO₃, 1.5 mL HCl, and 1.0 mL HF). All samples were dried and placed in a desiccator after cleaning by deionized water and ethanol. Macrographs of the specimens were imaged under a Leica digital optical microscope (S8 APO for low magnification, and DM4M for higher magnification). Finer scale investigation was completed with a Zeiss Auriga scanning electron microscope (SEM). Chemical composition analysis of the microstructural constituents was performed with a Zeiss Auriga SEM energy-dispersive spectroscopy (EDS) system.

The quasistatic tensile-shear, coach-peel, and cross-tension testing of the specimens (Fig. 2) was performed on a SUNS electromechanical test frame at a cross-head speed of 5 mm/min (Fig. 3) for photos of the experimental load train for each test. A minimum of seven replicates were completed for each condition.

Fig. 5 — Average weld nugget diameter and nugget thickness measurements (triangles and circles, respectively) as a function of electrode design.

Fig. 6 — Average weld thinning and distortion measurements (triangles and circles, respectively) as a function of electrode design.

Fig. 7 — Conceptual model of current distribution and heat dissipation with a MRD electrode.

Results and Discussion

Weld Morphology

Figure 5 is a series of photomicrographs of the 1.2-mm-thick AA6022-T4 to AA6022-T4 RSW specimen cross section along the centerline of the weld parallel to the coupon length and subjected to metallurgical preparation for each of the electrode designs. Indentations on the sheet surface from the MRD electrode are evident in Fig. 4B and C. The weld from the textured electrode (Fig. 4A) clearly exhibits two distinct weld nugget zones and a greater amount of distortion. Welds appear off-set toward the upper sheet or positive electrode in Fig. 4A and B, while eutectic stringers (i.e., whiskers) rich in alloy content were observed on the periphery of the weld nugget in the same.

The quantification of the effect of the electrode weld face design on

Fig. 8 — Representative weld nugget angles formed at the faying interface from different electrode geometries: A — Textured; B — MRD Ring H1; C — MRD Ring H2.

nugget diameter and thickness are presented in Fig. 5, and on thinning and distortion in Fig. 6. Figures 5 and 6 show that, compared to the MRD

electrode, weld nuggets produced using the textured electrode are slightly smaller in diameter, and have greater penetration or thickness, greater thin-

Table 3 — EDS-Based Chemical Composition at Various Points of the 'Eyelash' Microstructure

Spectrum	Elements (wt-%)				
	Al	Si	Mg	Fe	Cu
Nominal Value		0.8–1.5	0.45–0.7	0.05–0.2	0.01–0.11
1	84.3	12.5	0.8	—	2.4
2	87.2	7.8	0.8	2.0	2.2
3	77.8	18.4	1.0	—	2.8
4	70.7	21.2	2.2	1.3	4.6

effective weld face created a broader distribution of current — Fig. 7. This effect was accentuated with the greater ring height of MRD Ring H2 compared to MRD Ring H1. The larger contact area (see Table 2) and greater penetration of the MRD Ring H2 also created greater cooling at the weld perimeter, which acted to reduce the angle formed by the nugget at the faying interface compared to MRD Ring H1 (compare Fig. 8B and C, respectively).

Weld Microstructure

Figure 9 presents photomicrographs of weld microstructures developed by each of the three electrode face designs. The local solidification conditions (G = temperature gradient at the liquid/solid interface, and V = growth rate) at the liquid/solid interface is a function of the melt pool geometry and position of the liquid/solid interface, which themselves are functions of the electrode face design. For the purpose of this discussion, we define four microstructural zones based upon the resulting solidified crystal structure starting from the base metal to the center of the weld nugget: I — partially melted zone (PMZ), II — coarse columnar zone (CCZ), III — fine dendritic zone (FDZ), and IV — equiaxed zone (EZ) (Refs. 20–22).

The PMZ located just outside of the weld nugget boundary for all welds was characterized by relatively large recrystallized grains. This area exceeded the solidus temperature, but never fully reached the liquidus temperature during welding. Local grain boundary melting was visible in this area.

The CCZ was most prevalent for the textured electrode. It was produced adjacent to the nugget boundary. The CCZ occurs under conditions where decreasing current density caused by electrode indentation cannot provide sufficient heat to continue weld nugget growth. Weld nugget growth stalls, and as current density falls further, nugget recession occurs as solidification begins while weld current is still flowing. The shallow thermal gradients present under these conditions resulted in the formation of a coarse, columnar weld nugget structure with rejection of solute into the remaining molten pool. The textured electrode commonly produces this effect be-

Fig. 9 — Weld nugget microstructures from various electrode geometries: A — Textured; B — MRD Ring H1; C — MRD Ring H2. The weld nugget zones identified are the following: I — partially melted zone (PMZ), II — coarse columnar zone (CCZ), III — fine dendritic zone (FDZ), and IV — equiaxed zone (EZ). The five photomicrographs labeled a–d are higher magnification photos of specific areas highlighted by red boxes in Fig. 9A, and photomicrograph e is from Fig. 9B.

ning, and increased distortion. The textured electrode weld face does not penetrate as deeply into the upper sheet surface as the MRD Rings. The contact diameters for the welds in Fig. 4 are listed on Table 2.

These dimensions show that the average contact area for the textured electrode was somewhat smaller than that for both of the MRD electrodes. This effect was caused by the protruding rings of the MRD electrode, which acted to quickly spread current out during welding as successive rings came into contact with the sheet surface. Effectively, the MRD electrode operated as if it had less curvature (i.e., a higher radius of

curvature) than the textured electrode. This produced higher current densities for the textured electrode compared to the MRD electrodes. The higher current density created more heat within the weld, which enabled the weld nugget to grow out toward the electrode, accounting for the greater weld nugget penetration or thickness. In addition, the smaller effective radius of the curvature of the textured electrode was more effective at moving material laterally, accounting for the greater distortion and larger notch roots, which can affect mechanical performance of the joint.

The penetration of the rings of the MRD electrodes with its flatter-

Fig. 10 — Photomicrographs of weld microstructure and associated zone at weld nugget notch area welded by A — Textured; B — MRD Ring H1; C — MRD Ring H2. Zones defined as I: PMZ, II: CCZ, III: FDZ, and IV: ECZ.

cause it has a very large change in current density from the beginning to the end of the weld schedule, i.e., contact area is very small when current flow initiates, and it expands rapidly. In contrast, the MRD electrode has a larger contact area during initial current flow, which is caused by engagement of the protruding rings.

It was also observed that when the weld nuggets were offset toward the typically hotter positive electrode, the width of the CCZ on this side of the weld nugget was greater than that for the CCZ on the opposite side of the weld nugget, i.e., toward the negative electrode. Having the molten pool closer to the cooling effect of the electrode produced recession or local nugget solidification. The MRD Ring H2 exhibited negligible CCZ. In this case, the weld nugget was thin and further away from the cooling effect of the electrode weld face, and thus was less susceptible to recession. The MRD Ring H1 did exhibit a CCZ, but the size was somewhere in between that of the textured electrode and MRD Ring H2. Note that the weld schedule used in this study was designed for use with the MRD H2 tall-ring electrode, and thus was designed with the appropriate slope and pulsations to minimize recession.

Next to the CCZ is the FDZ. This zone is created by formation of a steep thermal gradient between the water-cooled welding electrode and weld nugget after termination of weld current. A fine-grained, harder dendritic structure is created. Eventually, as cooling progresses, an equiaxed dendritic zone is created. This occurs as the nugget is supercooled and dendrites solidify within the molten metal pool. This zone tends to be higher in alloy

Fig. 11 — Micromorphology of 'eyelashes' structure by SEM.

content due to rejection of alloy constituent from the CCZ as well as the FDZ and also shows precipitated phases.

Eutectic Stringers

The metallographic study also re-

vealed 'eyelash'-like microstructures emanating from the weld nugget and progressing radially outward through the heat-affected zone (HAZ) in the vicinity of the weld notch area for welds produced by Textured and MRD Ring H1 electrodes — Figs. 4, 10, and 11.

Fig. 12 — Schematic illustration of 'eyelash' formation mechanism: A — Partial melting in HAZ; B — cracking filling; C — alloy element segregation.

This phenomenon was not observed for welds produced with the MRD Ring H2 electrodes. Microstructural analysis identified a recrystallized microstructure with intergranular characteristics and dendritic morphology. This is considered to be subsolidus grain boundary liquation, which happens at temperatures generally above the eutectic temperature but below the equilibrium solidus temperature, and as such are referred to here as eutectic stringers.

It is known that rapid heating rates can cause local melting of grain boundary precipitants, and/or segregated alloy content. The EDS revealed segregation of alloying elements such as Si, Mg, Fe, and Cu at the grain boundaries (Table 3). Possible low-melting eutectics in Al-Mg-Si alloys, which may have contributed to the liquation, are listed in Table 4.

Another factor is the sharper effective radius of curvature for the textured and MRD-H1 electrodes compared to the MRD-H2 electrodes. This

may induce thermomechanical loading, which opens up the grain boundaries having grain boundary liquation. During the rapid cooling process, the metal contracted, developing tensile stress along the tangent of isotherms in the HAZ, which facilitates the opening up of grain boundaries with low-melting point constituents — Fig. 12.

The liquid in the nugget would eject under high pressure (i.e., loading from the electrode) through the mushy PMZ to fill up cracks in the HAZ before solidification was complete (Refs. 23–28). This may explain why the textured and MRD-H1 electrodes, which exhibited an effectively sharper radius compared to the MRD-H2 electrode, is associated with eutectic stringers while the MRD Ring H2 is not.

Mechanical Properties

A large number of factors that include the nugget diameter, sheet thinning, nugget porosity and porosity

distribution, microcracking, local microstructural features, notch root geometry as well as other features, control the mechanical performance of RSW joints. In this current work, three test geometries were investigated under static loading: tensile shear, cross tension, and coach peel. Subsequent work will investigate fatigue loading of these geometries.

Tensile shear. Figure 13A and B present tensile-shear strength and weld nugget diameter, as well as the energy at peak load for tensile-shear samples as a function of electrode face design. The average peak load and nugget diameter exhibited no statistically significant dependence upon the electrode face design, and all fracture modes were interfacial. There was no evidence of expulsion.

There was a noticeable difference in crack path between the textured and MRD electrodes. Figure 15 reveals that for textured electrode specimens, which experienced a significant amount of recession and CCZ formation, the crack initiated at the perimeter of the nugget at the faying interface within the CCZ, and propagated along the length of the grains in the CCZ boundary. It then changed paths upon meeting the FDZ to progress along the CCZ/FDZ boundary. Finally, both penetrated into the FDZ/EZ and combined for complete fracture of the specimen.

For specimens welded with MRD Ring H1 and H2 electrodes, recession and CCZ formation was much more limited. This affected weld nugget fracture during tensile-shear testing. The cracks propagated through the FDZ, which formed a shell along the perimeter of

Table 4 — Possible Low-Melting Eutectics in Al-Mg-Si Alloys

Eutectics	Melting Temperature (°C)
Al-Mg ₂ Si	595
Al-Si	579
Al-Mg ₂ Si-Si	559
Al-Mg ₂ Si-(FeMn) ₃ Si ₂ Al ₁₅ -Si	< 550
Al-Mg ₂ Si-FeMg ₃ Si ₆ Al ₈ -Si	549
Al-Mg ₂ Si-(CrFe) ₄ Si ₄ Al ₁₃ -Si	< 550
Al-CuAl ₂ -Mg ₂ Si	514
Al-Cu ₂ Mg ₈ Si ₆ Al ₅ -CuAl ₂ -Si	507

Fig. 13 — A — Tensile-shear strength and weld nugget diameter; B — energy at peak load as a function of electrode face design (textured, MRD Ring H1, and MRD Ring H2).

the nugget at the faying interface, followed by the EZ — Fig. 14. This fine-dendritic area appeared to absorb more energy compared to the CCZ structure, as shown by the data in Fig. 13 for textured and MRD electrodes.

Cross tension. Figure 15 presents cross-tension strength and weld nugget diameter as a function of electrode face design. The average nugget diameter exhibited no statistically significant dependence upon electrode face design. However, the average peak load for the MRD Ring H2 was significantly lower than that for either the textured or MRD Ring H1 electrodes. The fracture modes of all electrode geometries were button pull-out. However, two propagation paths were observed. The textured specimens (Fig. 16A) exhibited crack initiation and propagation along the larger grains of the CCZ similar to the tensile-shear specimens. The crack then proceeded into the EZ until the bending of the coupon forced a change in the preferred crack path direction, perpendicular to the sheet surface. For both MRD Ring H1 and H2 electrodes, the crack did not penetrate the FDZ. This is most likely due to the much finer dendritic structure providing greater strength than the CCZ. The path followed along the weld nugget periphery where the strength was reduced in the PMZ (Fig. 16B and C) until the point of mechanical loading due to bending of the coupon, which forced a change in the preferred crack path direction perpendicular to the sheet surface.

Fig. 14 — Crack path within fractured tensile-shear specimens as a function of weld nugget and electrode face design (textured, MRD Ring H1, and MRD Ring H2).

Fig. 15 — Cross-tension strength and weld nugget diameter as a function of electrode face design (textured, MRD Ring H1, and MRD Ring H2).

The reduced cross-tension strength for specimens welded by the MRD Ring H2 electrode is related to the weld nugget structure produced at the

faying interface. The weld nugget had a shallow angle at the faying interface when using the MRD Ring H2, thus there was a more direct crack path that

Fig. 16 — Crack path within fractured cross-tension specimens as a function of electrode face design: A — Textured; B — MRD Ring H1; C — MRD Ring H2.

would have facilitated propagation and a lower cross-tension strength because the weld nugget diameters were comparable. Furthermore, the MRD Ring H2, having a greater ring height, also penetrated deeper into the substrate, such that as the crack propagated along the PMZ and changed direction as it moved beneath a ring indentation, there was a shorter distance for the crack to travel through the substrate (Fig. 17C), and ultimately fractured in the groove left by the ring.

Coach peel. Figure 18 presents coach-peel strength and weld nugget diameter as a function of electrode face design. The average nugget diameter exhibited no statistically significant dependence upon electrode face design. The average peak loads for all three sets of tests fell within their respective error bands. In general, the load displacement curve reached an initial peak followed by a load drop, which is the point of crack initiation. For MRD Ring H2, the load then increased slightly as crack propagation proceeded around the weld nugget until a second peak load was reached, after which the load dropped and the

coupon fractured. All coupons fractured via button pullout mode.

Figure 19 shows the crack paths observed for coach-peel specimens. All three electrode designs produced button pullout. However, the crack paths were somewhat different. Both MRD electrodes produced the FDZ at the perimeter along the faying interface. This stronger structure was able to deflect the crack and form weld buttons during coach-peel testing. Welds made with the textured electrode behaved differently. The cracks first penetrated the outer, weak CCZ (Fig. 19A) and were then deflected by the stronger FDZ structure within the nugget to form a weld button.

Specimens welded by the MRD Ring H1 exhibited a somewhat higher coach-peel strength than either the textured or MRD Ring H2 electrode. The MRD Ring H1 weld nugget microstructure (Figs. 10 and 19B) is a good compromise between the large columnar dendritic region of the textured electrode weld (which favors easy crack growth along the columnar grain boundaries and then into the fine-dendritic zone — Fig. 19A), and the flatter weld nugget creat-

ed by the MRD Ring H2 (which facilitates initial crack propagation along the PMZ — Fig. 19C). Neither the ‘eyelash’ microstructure in the HAZ, nor the cracks within the weld nugget, influenced crack path.

Summary and Future Work

This paper explores, through microstructural analysis and mechanical property testing, the effect of electrode face design upon the resistance spot welding of 1.2-mm-thick 6022-T4 aluminum sheet welded to itself. For each of the electrode designs, cross-sectioned samples were made to measure the nugget diameter, thickness, angles, weld thinning, distortion, and contact diameter. This was supplemented by mechanical tests, including tensile shear, cross tension, and coach peel, performed on welds from each of the three electrode geometries.

The textured electrode responds as if it had a sharper radius of curvature compared to the MRD electrodes because of greater penetration, thinning, and distortion. The textured electrode also exhibited the largest CCZ struc-

Fig. 17 — Crack length within fractured cross-tension specimens as a function of electrode face design: A — Textured; B — MRD Ring H1; C — MRD Ring H2.

Fig. 18 — A — Coach-peel strength and weld nugget diameter as a function of electrode face design (textured, MRD Ring H1, and MRD Ring H2); B — load displacement curves for MRD Ring H2 welds.

ture, which reduced the tensile shear energy absorption at peak load compared to the MRD electrode designs. MRD Ring H2 had the greatest penetration of the rings with their associated cooling effect, and consequently exhibited the smallest nugget angles at the faying interface, leading to reduced cross-tension strength. Of the designs investigated, the MRD design, Ring H1, provided the best performance because of its ability to create larger nugget diameters and robust microstructures for a given electrode size and weld schedule.

'Eyelash'-like microstructures were found for welds produced by textured and MRD Ring H1 electrodes and were attributed to subsolidus grain boundary liquation. Neither the 'eyelash' microstructure in the HAZ nor cracks within the weld nugget influenced crack path.

Subsequent work will investigate

fatigue performance of welds with varying electrode designs, and optimization of the MRD electrode face topography will be considered.

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Fig. 19 — Crack path within fractured coach-peel specimens as a function of electrode face design: A — Textured; B — MRD Ring H1; C — MRD Ring H2.

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Table A — Nugget Diameter and Thickness Referred in Fig. 5

Sample No.	Diameter (Unit: mm)			Thickness (Unit: mm)		
	Textured	MRD Ring H1	MRD Ring H2	Textured	MRD Ring H1	MRD Ring H2
Sample 1	5.68	6.03	6.34	1.39	1.46	1.08
Sample 2	5.70	5.95	5.72	1.69	1.39	0.89
Sample 3	5.86	5.81	5.78	1.49	1.28	1.01
Ave.	5.75	5.93	5.95	1.52	1.38	1.00
Std.	0.08	0.09	0.28	0.12	0.07	0.08

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Appendix

Raw data including nugget diameter, thickness, weld thinning, distortion, and total energy, as well as lap-shear, coach-peel peak force, and cross-tension peak force for the welds in the experiments are displayed. The Ave. and Std. represent the mean value and standard deviation of all tested samples, respectively.

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Table B — Weld Thinning and Distortion Referred in Fig. 6

Sample No.	Thinning (Unit: mm)			Distortion (Unit: mm)		
	Textured	MRD Ring H1	MRD Ring H2	Textured	MRD Ring H1	MRD Ring H2
Sample 1	0.35	0.26	0.09	0.27	0.22	0.07
Sample 2	0.35	0.22	0.15	0.27	0.23	0.07
Sample 3	0.35	0.22	0.22	0.32	0.2	0.1
Ave.	0.35	0.23	0.15	0.29	0.22	0.08
Std.	0.00	0.02	0.05	0.02	0.01	0.02

Table C — Tensile-Shear Peak Force and Total Energy Referred in Fig. 13

Sample No.	Peak Force (Unit: N)			Total Energy (Unit: J)		
	Textured	MRD Ring H1	MRD Ring H2	Textured	MRD Ring H1	MRD Ring H2
Sample 1	3156	3143	2896	1.31	1.51	1.12
Sample 2	3106	3089	2945	1.25	1.34	1.62
Sample 3	3099	3420	3104	1.16	1.74	1.54
Sample 4	3149	2941	3319	1.25	1.40	1.67
Sample 5	3129	3129	3258	1.14	1.67	1.66
Sample 6	3000	3049	2824	1.02	1.43	1.20
Sample 7	3092	3248	3225	1.11	1.46	1.42
Ave.	3104	3146	3081	1.17	1.51	1.46
Std.	48	142	180	0.09	0.14	0.21

Table D — Cross-Tension Peak Force Referred in Fig. 15

Sample No.	Cross-Tension Peak Force (Unit: N)		
	Textured	MRD Ring H1	MRD Ring H2
Sample 1	2026	2016	1581
Sample 2	2234	1931	1652
Sample 3	2359	2127	1589
Sample 4	2039	1860	1692
Sample 5	1867	1881	1491
Sample 6	2020	1960	1652
Sample 7	2012	2175	1483
Ave.	2080	1993	1592
Std.	151	111	75

Table E — Coach-Peel Peak Force Referred in Fig. 18

Sample No.	Coach-Peel Peak Force (Unit: N)		
	Textured	MRD Ring H1	MRD Ring H2
Sample 1	513	420	394
Sample 2	426	473	425
Sample 3	432	473	455
Sample 4	393	442	501
Sample 5	434	451	394
Sample 6	448	479	415
Sample 7	409	550	443
Ave.	436	470	433
Std.	35	36	35